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Dielectric Properties of Ponderosa Pine at High Frequencies

By

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Wood Technologist, Oregon Forest Products Laboratory

Bulletin No. 29

September 1949

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In Cooperation with
Oregon Forest Products Laboratory

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I. INTRODUCTION

The use of high frequency energy as a source of heat to cure synthetic resin glue lines in wood assemblies is comparatively new to the wood products industry. To facilitate the proper use of this form of energy, it is essential that a more complete knowledge of the dielectric properties of wood be made available. These properties, namely, dielectric constant and power factor, must be known in order to determine the optimum circuit conditions for a particular process and material.

A previous study (1) of the dielectric properties of Douglas fir has led to a similar study for Ponderosa pine (*Pinus ponderosa* Lawson). Both of these woods are widely used in the manufacture of wood products in Oregon and the remainder of the Pacific Northwest region. The purpose of this bulletin is to present extensive data for the dielectric constant and power factor of Ponderosa pine. The data are presented in terms of four variables: (1) frequency, (2) moisture content, (3) specific gravity, and (4) grain direction.

Much of the detail concerning dielectric heating theory and the analysis of data obtained from measurements to determine the power factor and dielectric constant has been omitted from this bulletin. The reader is referred to a previous bulletin (1) for a complete presentation of these sections. In addition, the previous bulletin contains a section on design considerations that presents much useful information.

II. DIELECTRIC HEATING

1. **The electric field.** Whenever a potential difference (or voltage) is impressed on two electrodes, an electric field is produced in the medium between the electrodes. This medium in which the electric field exists is called a "dielectric." Various materials have different dielectric properties, and hence the electric field will have different characteristics in different media. Two of these dielectric

properties that are important in dielectric heating are the "dielectric constant" and "power factor" of the dielectric. It is necessary that both of these quantities be determined in order to perform calculations for a particular dielectric material.

2. Power loss in a dielectric. If a d-c voltage is applied between two electrodes, a static electric field will be set up. If the dielectric material is not a perfect insulator there will be a small conduction current flowing through the dielectric. This will cause power to be produced in the dielectric material equal to the product of the voltage times the current. Such power loss in the dielectric material will be called "conduction loss."

If a high-frequency alternating voltage is applied between the electrodes, the conduction loss still occurs though it may be somewhat different in magnitude from that for an applied d-c voltage. However, in addition to the conduction loss there will be another component of power produced with a-c voltage that was not present when a d-c voltage was applied. This additional loss will be called "dielectric loss."

When a-c voltage is applied to the electrodes, the resultant rapid alternation of the electric field produces changing stress conditions in the dielectric material. This causes a loss of power within the dielectric. Dielectric materials that possess good insulation qualities may have a very small conduction loss but a rather large dielectric loss. It is the power produced due to dielectric loss that is of chief interest in the dielectric heating problem.

An analysis of dielectric loss (1) yields the following relationship amongst the variables that must be considered in a dielectric heating problem.

Power

$$\text{density} = 1.414 \times 10^{-12} (pf)(\epsilon)(f)(grad E)^2 \text{ watts per cu in.} \quad (1)$$

pf = power factor of the dielectric.

ϵ = dielectric constant of the dielectric.

f = frequency in cycles per second.

$grad E$ = potential gradient in rms volts per inch.

It will be noted from equation (1) that the power density increases directly with the frequency for a fixed value of potential gradient. However, the power factor and dielectric constant of most materials varies with frequency. Hence, these quantities must be determined at the frequency to be used. Generally it will be found that the product of power factor and dielectric constant does not vary widely with frequency over a small range of frequencies.

III. DIELECTRIC PROPERTIES OF PONDEROSA PINE

1. **Variables that affect dielectric properties.** A considerable amount of preliminary data was obtained in a previous study of Douglas fir to determine the major variables affecting the dielectric properties of wood. The results indicated that the following variables had a major effect upon the dielectric constant and power factor:

- (a) Frequency,
- (b) Moisture content,
- (c) Wood density,
- (d) Grain direction.

2. **Frequency.** Data were taken in the frequency range from two to forty megacycles per second. The dielectric constant and power factor data are presented on graphs as a function of frequency. Within the frequency range investigated, the dielectric constant decreases with increasing frequency while the power factor shows an increase.

3. **Moisture content.** The moisture content of the wood is expressed as a per cent of the oven dry weight of wood. Data were taken for nominal moisture contents of oven-dry, 4, 10, and 15 per cent. The data are presented by graphs, each depicting a different moisture content. The dielectric constant shows a large increase as the moisture content is increased from oven-dry to 15 per cent. The power factor in general shows a lesser increase as the moisture content increases in this range.

4. **Wood density.** The specific gravity of the wood at oven-dry condition was measured. Data were obtained on wood samples having nominal specific gravities of 0.35, 0.40, and 0.45 and are plotted as three sets of curves on each graph. The more dense wood has a greater value of dielectric constant and generally a somewhat larger value of power factor.

5. **Grain direction.** Vertical grain wood has a grain direction perpendicular to the electrode surfaces and parallel to the electric field. Flat grain wood has a grain direction parallel to the electrode surfaces and perpendicular to the electric field. Data were obtained for both grain directions, and two curves (one for each grain direction) are plotted in each set on the graphs.

The effect of grain direction upon the dielectric properties of Ponderosa pine does not appear to be as significant as for Douglas

fir. Whether or not this is characteristic of the less dense woods cannot be determined without additional data on other species. In general the woods tested have exhibited a greater value of power factor and dielectric constant for vertical grain. An exception to this is noted for medium density Ponderosa pine. At oven-dry conditions the dielectric constant is greater for vertical grain, but as the moisture content is increased the data cross over and at the higher moisture contents the flat grain specimens exhibit the larger value of dielectric constant. The power factor is slightly greater for flat grain at all moisture content values.

The specimens tested appeared normal in every respect, but there is a possibility that minor variations not considered might have caused this exception because the difference between dielectric properties of vertical grain and flat grain Ponderosa pine is slight.

6. Temperature. The dielectric constant and particularly the power factor of a piece of wood tend to change as the temperature rises during the heating cycle. Normally, slight circuit adjustments must be made during the heating cycle if the input power is to be held constant. All data in this bulletin were taken at temperatures near normal room temperature. Hence, design calculations using these data are for the initial conditions existing at the start of the heating cycle.

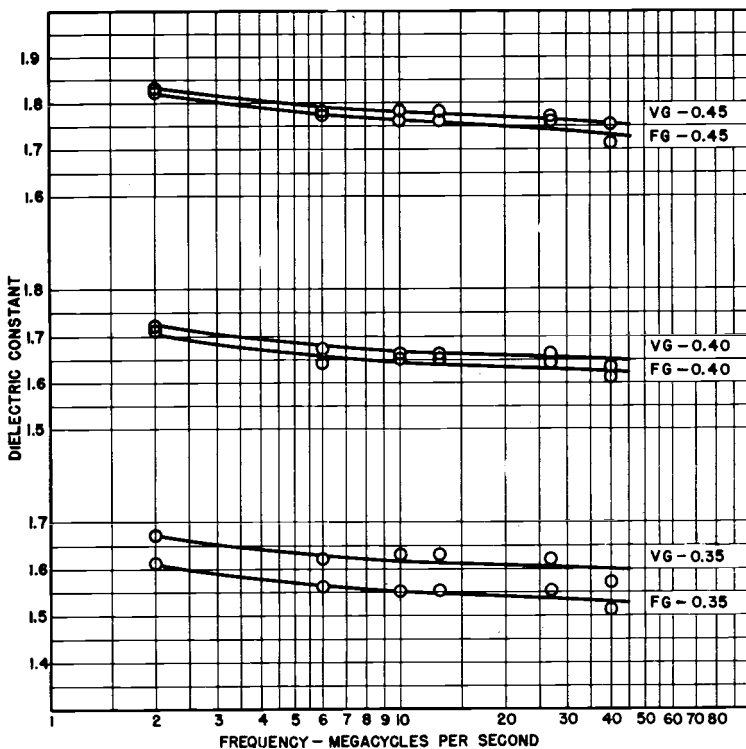


Figure 1. Dielectric constant of oven-dry Ponderosa pine. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

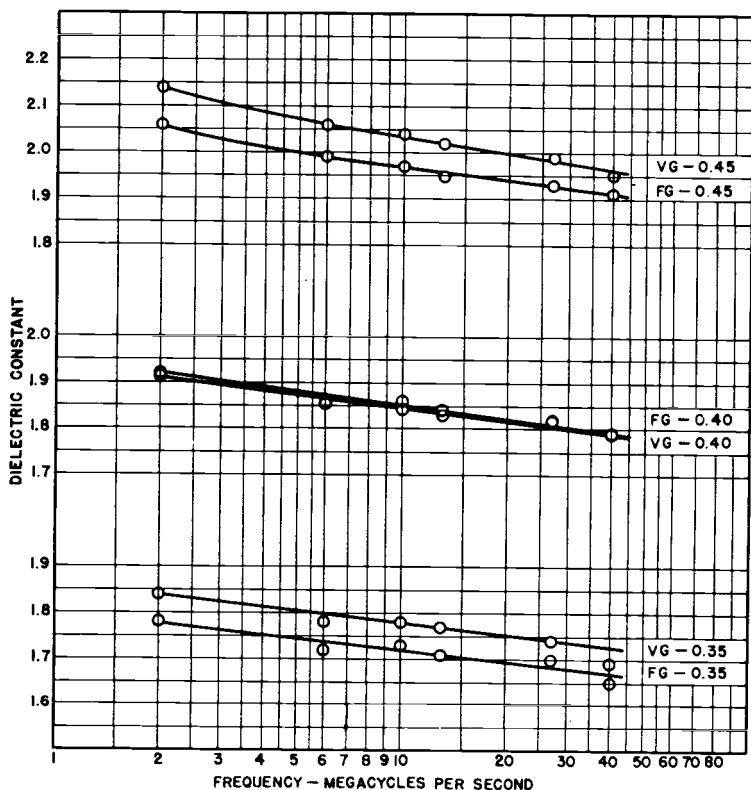


Figure 2. Dielectric constant of Ponderosa pine at 4% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

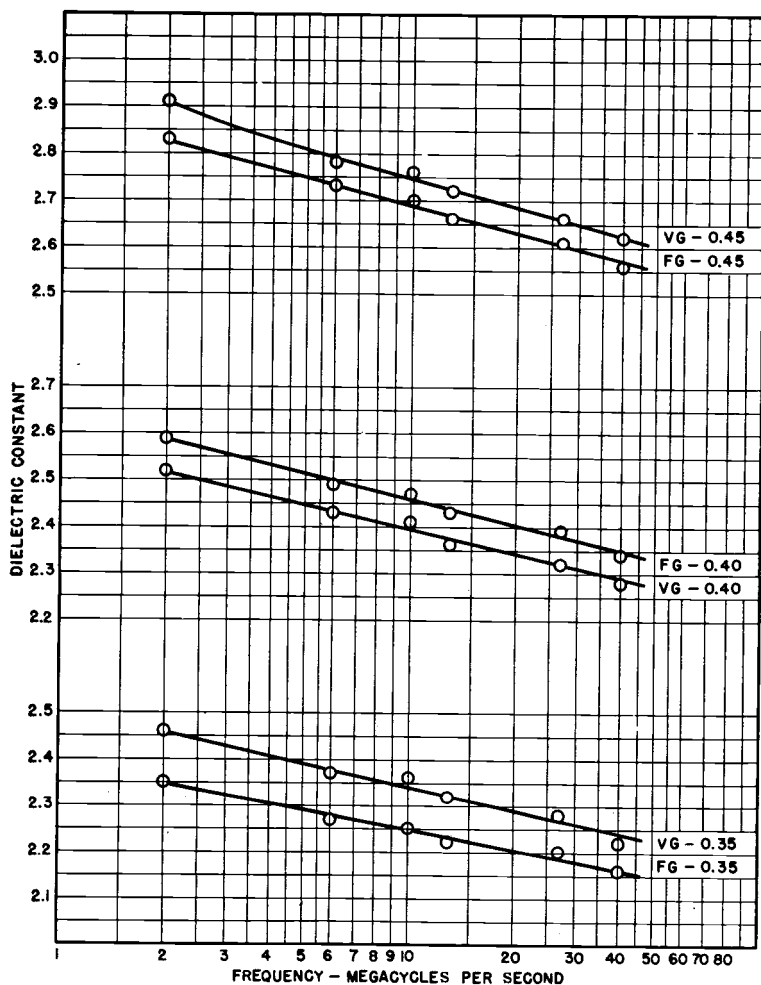


Figure 3. Dielectric constant of Ponderosa pine at 10% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

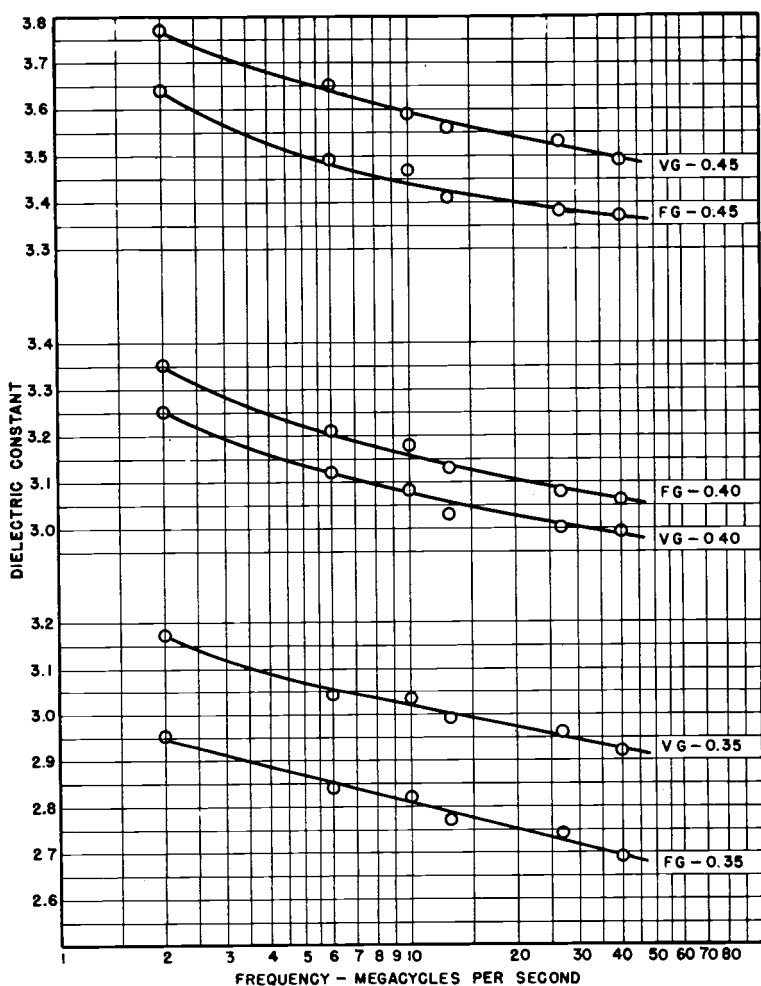


Figure 4. Dielectric constant of Ponderosa pine at 15% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

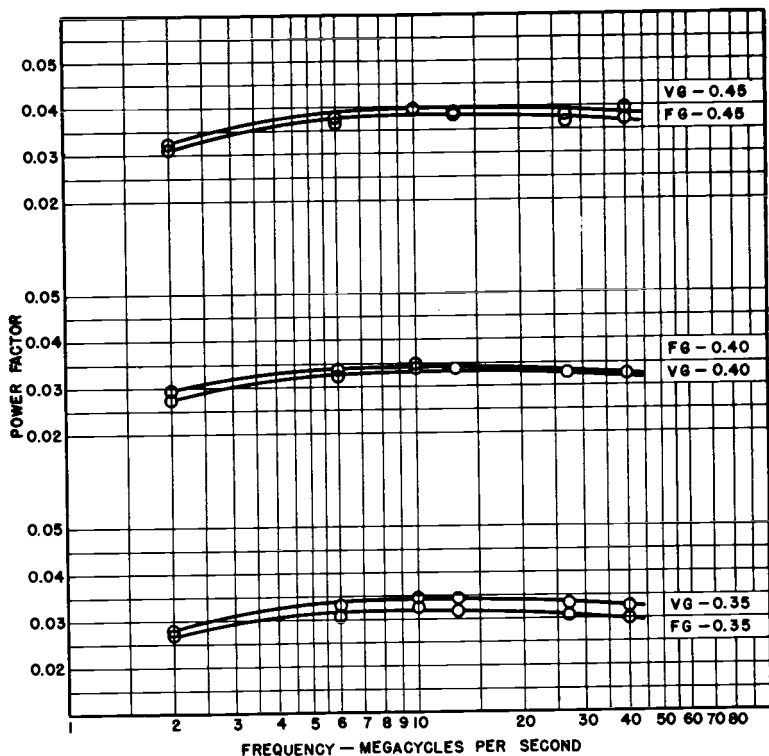


Figure 5. Power factor of oven-dry Ponderosa pine. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

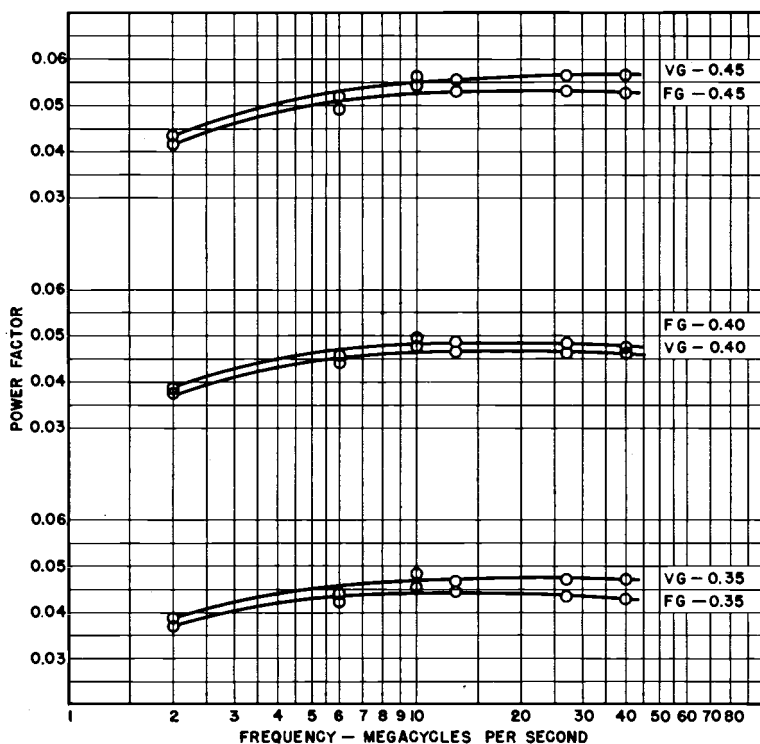


Figure 6. Power factor of Ponderosa pine at 4% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

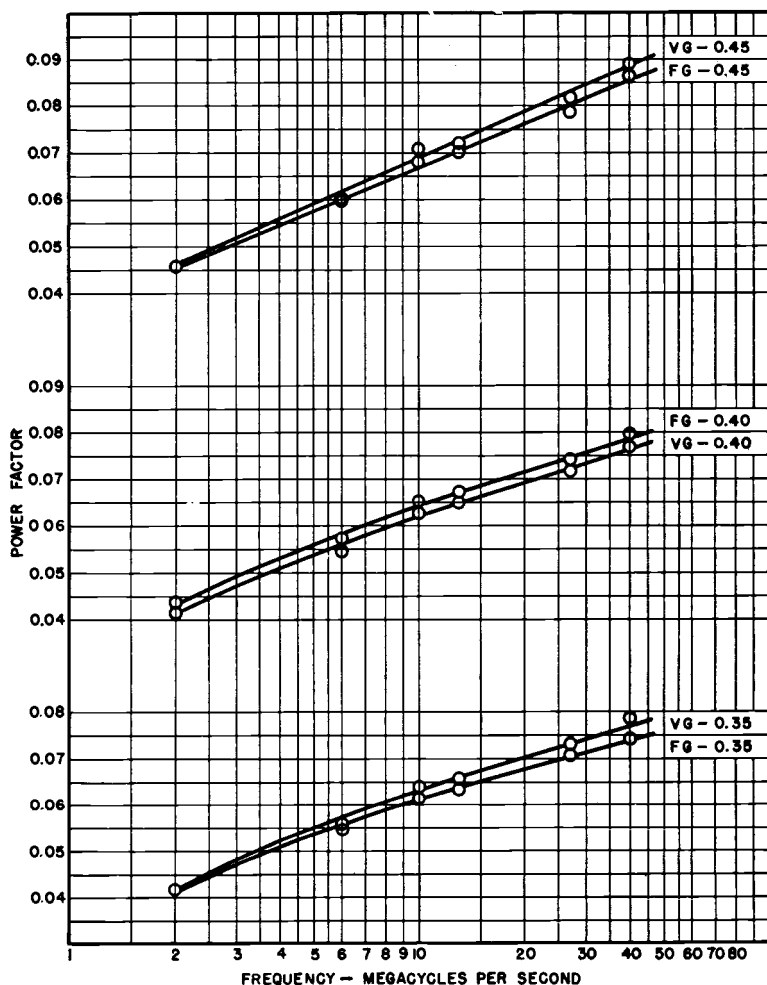


Figure 7. Power factor of Ponderosa pine at 10% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

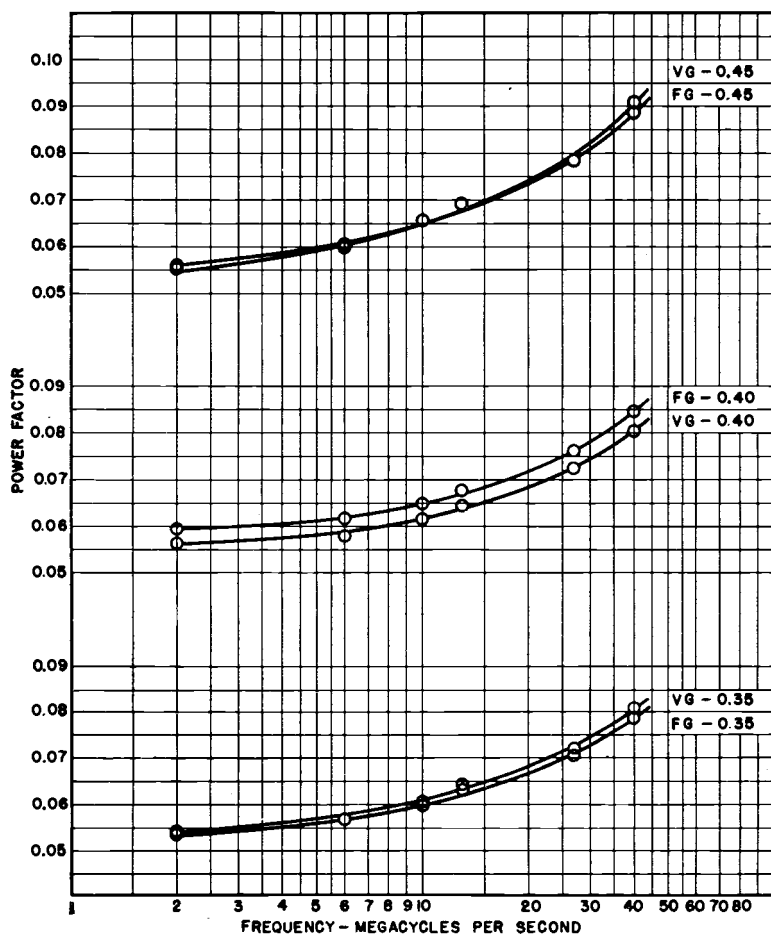


Figure 8. Power factor of Ponderosa pine at 15% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

IV. Procedure

1. **Selection of samples.** As a result of the previous work on Douglas fir (1), it was determined that the dielectric properties of wood are primarily affected by the following wood variables:

- (a) Moisture content,
- (b) Specific gravity,
- (c) Grain direction.

Variation in amount of sapwood and heartwood, growth site, fungus stain, other discolorations, and presence of small pitch streaks were found to have negligible effect on the dielectric properties. As a result of the foregoing disclosures, sample categories were established to include specimens that would be representative of the normal range of specific gravity found in Ponderosa pine. Nominal values for specific gravity were set at 0.35, 0.40, and 0.45. Each of these categories were represented by five flat grain specimens (grain oriented parallel to electrode surfaces), and five vertical grain specimens (grain oriented perpendicular to electrode surfaces). This comprised a total requirement of 30 sample pieces.

2. **Preparation of samples.** Sample pieces were cut from kiln dried billets 0.5 inch thick by two or more feet long having a moisture content of 8 per cent. The billets, cut from rough timber, were selected to be consistent with established requirements for direction of grain and range of specific gravity. Moisture content was maintained at 8 per cent, the midpoint of variation during testing, so that dimensional change would be minimized as the moisture content was varied.

Samples were cut 4 inches square by 0.25 inch thick with a tolerance of ± 0.003 inch. After cutting and extremely light sanding of the edges to remove loose fibers, the samples were reconditioned to 8 per cent moisture content. Weights were then taken and the approximate specific gravity of each individual piece was determined on the basis of calculated oven-dry weight. Selection of the final 30 samples was made from a larger quantity of original specimens and was based on the physical appearance and specific gravity of individual pieces.

3. **Establishing moisture content values.** To enable investigation of the effect of varying moisture content on dielectric properties, samples were tested at nominal values near oven-dry, 4, 10, and 15 per cent. The upper limit of this range was selected as being consistent with the requirements of most synthetic resin adhesives

and with the practical maximum moisture content desirable with dielectric heating of wood.

Samples were conditioned in two steps. First, they were brought to the desired moisture content value in a small experimental dry kiln. This procedure amounted to pre-conditioning. Second, the samples were confined in desiccators in which saturated salt solutions were used to maintain desired equilibrium conditions (2). During this period of conditioning, temperature was established as near to normal room temperature as the nature of the particular salt solution would permit. Each desiccator (Figure 9) was equipped with a fan for air circulation and an agitating paddle in the salt solution, thereby obtaining the maximum effect from the solution and avoiding air stratification within the chamber.

Moisture content values were established at temperatures near room temperature. Oven-dry samples, which were necessarily exposed to a temperature of 212 F, were wrapped in aluminum foil and allowed to cool to room temperature in desiccators before electrical measurements were made.

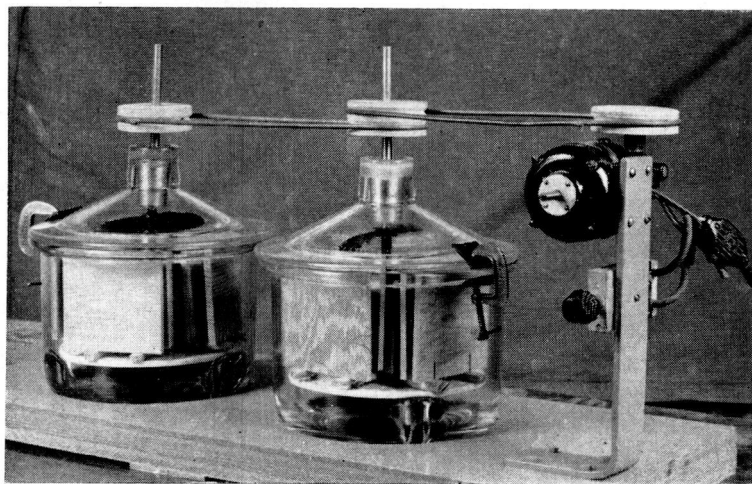


Figure 9. Moisture conditioning apparatus.

4. **Determination of specific gravity.** Original grouping of samples, as described previously, was based on a specific gravity value for oven-dry Ponderosa pine derived from the calculated oven-dry weight and calculated volume of each sample. At the termination of testing, the samples were oven dried, weighed, and immersed in mer-

cury as a means of measuring volume by displacement. All data in this bulletin are based on true values for specific gravity established by the final procedure.

5. **Q-meter.** All electrical measurements were made with a Boonton Radio Corporation Type 160-A Q-meter. This instrument may be used for determining dielectric properties of materials in the frequency range from 50 kilocycles to 75 megacycles per second. Fundamentally, the measuring circuit consists of a series circuit which may be adjusted to resonance with a calibrated variable capacitor. Plug-in coils having different inductances are used to cover the wide frequency range. A built-in vacuum tube voltmeter measures the voltage across the variable capacitor and is calibrated to indicate the Q of the entire series circuit.

6. **Press.** A small press to hold the wood sample was constructed with parallel brass plate electrodes four inches square. A screw arrangement is provided so that considerable pressure can be placed on the sample after it is inserted between the electrodes. The bottom electrode is insulated and supported by four polystyrene columns 0.75 inch diameter and 1.25 inches high. The press sits atop the Q-meter and has two short 0.75 inch wide copper straps connecting the electrodes to the Q-meter terminals.

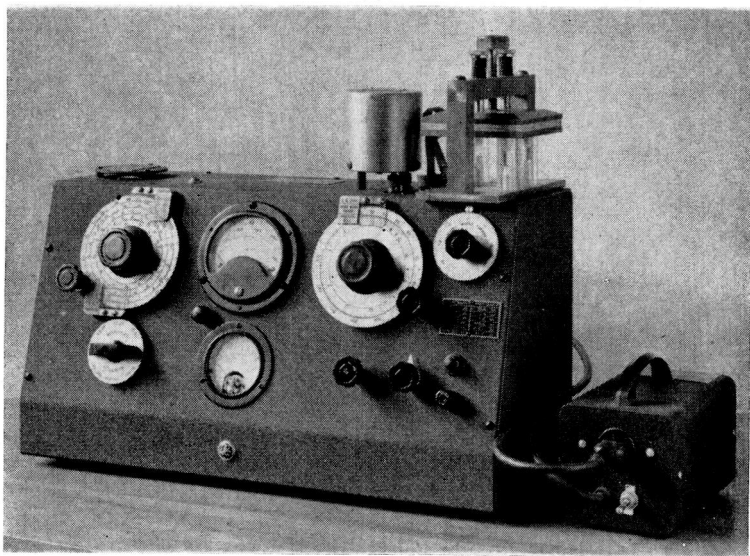


Figure 10. Boonton Q-meter and accessories.

The photograph, Figure 10, shows the Q-meter with all accessories in normal position. The shielded coil is at the left atop the Q-meter and the press with a sample in place is at the right. A constant-voltage transformer, shown alongside the Q-meter, is required so that changes in line voltage do not affect the Q-meter calibration.

7. Electrical measurements. Any set of electrodes to hold the sample while taking measurements will inherently have distributed inductance and capacitance and may have small losses. These either must be kept very small or data must be taken in such a manner as to account for these electrode constants, otherwise the accuracy of the results will not be good. The higher the frequency of measurement, the more difficult is the problem of minimizing the effects of the distributed inductance and capacitance of the electrodes and associated leads. Therefore, a method of taking data to account for these effects was worked out. All data for this bulletin were taken in this manner.

It is necessary to take three sets of readings from the Q-meter to account for the distributed constants of the press and determine accurately the dielectric properties of the wood sample.

- (1) Observe the Q reading and the calibrated capacitor setting at resonance with the coil in place but without the press connected.
- (2) Observe the calibrated capacitor setting at resonance with both the coil and press connected but without a sample in place. The press must be adjusted so that the electrode spacing is equal to the sample thickness for this measurement.
- (3) Observe the Q reading and the calibrated capacitor setting at resonance with both the coil and press connected and with a sample in place.

An analysis of the required measurements results in the following expressions. A complete derivation of these is included in the bulletin on Douglas fir (1).

$$Q_x = \frac{(C_2 - C_3 + C_e)(Q_1 Q_3)}{C_1(Q_1 - Q_3)} \quad (2)$$

$Q_x = Q$ of the wood dielectric.

C_1 , C_2 , and C_3 = capacitance of the Q-meter calibrated variable capacitor for parts (1), (2), and (3) respectively as listed above.

C_e = the direct capacitance between the electrode faces when the spacing between them equals the sample thickness. It may be calculated from equation (3).

Q_1 and $Q_3 = Q$ readings for parts (1) and (3) respectively as listed above.

$$C = \frac{0.225A}{s} \text{ micro-microfarads} \quad (3)$$

A = area of one electrode in square inches.

s = distance between electrodes in inches.

The power factor of the dielectric and Q_x are related as in the following expression:

$$pf = \frac{1}{\sqrt{1 + Q_x^2}} \quad (4)$$

If the value of Q_x is greater than about 10, the value of the power factor becomes essentially equal to the reciprocal of Q_x .

$$pf = \frac{1}{Q_x} \text{ if } Q_x > 10 \quad (5)$$

The dielectric constant is determined from equation (6) where the quantities indicated are the same as for equations (2) and (3).

$$\epsilon = 1 + \frac{4.45(C_2 - C_3)s}{A} \quad (6)$$

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